ONR Final Report
"Models of Working Memory"

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"Working memory" is a basic cognitive mechanism (or set of mechanisms) that is responsible for keeping track of multiple task-related goals and subgoals, or integrating multiple sources of information. As such, it is essential for any complex cognitive task, such as planning an airplane's route or learning new computer software. Understanding the mechanisms and structures underlying working memory is, hence, one of the most important scientific issues that need to be addressed to improve the efficiency and performance of individuals on such cognitive tasks in a technological setting A good understanding of working memory should lead to effective practical applications, such as the design of better computer interfaces, and novel techniques for training new personnel on complex information processing tasks.

The Office of Naval Research provided funds to cover part of the travel and subsistence expenses for a symposium entitled *Models of Working Memory* that was held July 9-13, 1997 in Boulder, Colorado. The symposium was hosted by the Instititute for Cognitive Science (ICS) at the University of Colorado, Boulder and there was some additional support provided by the ICS as well as the Council on Research and Creative Work (CRCW) at the University of Colorado.

The goal of the symposium was to promote a better understanding of the architecture and mechanisms that underlie working memory as well as the practical implications of these important issues. The symposium was specifically dedicated to detailed systematic comparisons of existing models and theories of working memory. Thus, we included several features that would facilitate active communication and collaborative problem solving among participants during the symposium. Specificially, we used an issue-based approach to theory comparison, in which each participant addressed a common set of important theoretical questions that have been guiding the current research in the field. These questions addressed a wide range of theoretical issues in working memory, including (1) the basic mechanisms and representations in working memory, (2) the control and regulation of working memory, (3) the nature of working memory limitations, (4) the unitary vs. non-unitary nature of working memory, (5) the role of working memory in complex cognitive activities, (6) the relationship of working memory to long-term memory and knowledge, (7) the relationship of working memory to attention and consciousness, and (8) the biological implementation of working memory. In addition to this issue-based approach to theory comparison, we included long discussion periods following each talk, led by designated discussion leaders. Furthermore, we also included several "specific" commentators whose role was to provide commentaries across different theories on the answers to specific theoretical questions as well as two "general" discussants who provided general commentaries evaluating the current status of the field.

As we hoped, this type of issue-based appraoch to theory comparison and evaluation led to much active communication and collaborative problem solving among participants during the symposium and to fruitful theoretical synthesis of currently disparate claims about working memory. Several similarities among diferent theories that had not previously been recognized were discussed. For example, the importance of the control mechanism of working memory, shared by all theories, was highlighed by the symposium discussion, as well as the view that active maintenance of information in working memory is in the service of complex cognition, rather than simple memorizing. Indeed, such emphasis on executive

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Re: Final Report of "Models of Working Memory"

Enclosed are four copies of the formal report of the "Models of Working Memory" symposium (N00014-97-1-0547). If you need any further information, please let me know.

Sincerely,

Akira Miyake, Ph.D.
Assistant Professor of Psychology

control and active maintenance of working memory led us to change the title of the companion volume from *Models of Working Memory* to include *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control.* (See below for more discussion of the general consensus we achieved at the symposium.) Another measure of the success of this approach was that several participants began the process of integrating other people's ideas into their own theoretical frameworks, or proposing new collaborations between research groups. In general, we believe the symposium was quite successful in fulfilliing the goal that we originally set for the symposium.

Symposium Attendees and Participants.

The symposium was attended by a number of leading researchers in working memory from around the world. These researchers included:

1. Alan Baddeley (University of Bristol
2. Philip Barnard (MRC Applied Psychology Unit)
3. Todd Braver (Carnegie Mellon University)
4. Susan Chipman (Office of Naval Research)
5. Jonathan Cohen (Carnegie Mellon University)
6. Nelson Cowan (University of Missouri)
7. Meredyth Daneman (University of Toronto)
8. Randall Engle (Georgia Institute of Technology)
9. Anders Ericsson (Florida State University)
10. Helen Gigley (Office of Naval Research)
11. Alice Healy (University of Colorado)
12. Mary Hegarty (UC-Santa Barbara)
13. Marcel Just (Carnegie Mellon University)
14. Michael Kane (Georgia State University)
15. David Kieras (University of Michigan)
16. Walter Kintsch (University of Colorado)
17. Richard Lewis (Ohio State University)
18. Marsha Lovett (Carnegie Mellon University)
19. David Meyer (University of Michigan)
20. Akira Miyake (University of Colorado)
21. Robert Logie (University of Aberdeen)
22. Randall O'Reilly (University of Colorado)
23. Bruce Pennington (University of Denver)
24. Lynne Reder (Carnegie Mellon University)
25. Timothy Salthouse (Georgia Institute of Technology)
26. Priti Shah (University of Memphis)
27. Walter Schneider (University of Pittsburgh)
28. Richard Young (University of Hertfordshire)

Symposium Schedule.

<u>Wednesday, July 9</u>

7:30	Opening Evening Reception (at the Broker Inn)

<u>Thursday, July 10</u>

7:30-8:00	Breakfast
8:00-8:15	Opening Remarks by the Organizers (Akira Miyake & Priti Shah)
8:15-9:15	Alan Baddeley & Robert Logie

	"The Multiple Component Model of Working Memory"
9:15-9:45	Discussion of Baddeley & Logie (Discussion Leader: Meyer & Kieras)
9:45-10:05	Coffee Break
10:05-10:45	Nelson Cowan "The Embedded Processes Model of Working Memory"
10:45-11:15	Discussion of Cowan (Discussion Leader: Schneider)
11:15-11:55	Randy Engle, Steve Tuholski, & Michael Kane "The Resource-Inhibition Model of Working Memory"
11:55-12: 25	Discussion of Engle, Tuholski, & Kane (Discussion Leader: Ericsson)
12:25-1:50	Lunch
1:50-2:30	Marsha Lovett, Lynne Reder, & Christian Lebiere "Modeling Working Memory in a Unified Architecture"
2:30-3:00	Discussion of Lovett, Reder, & Lebiere (Discussion Leader: Barnard)
3:00-3:20	Coffee Break
3:20-4:00	Richard Young & Rick Lewis "Soar Perspective on Working Memory"
4:00-4:30	Discussion of Young & Lewis (Discussion Leaders: O'Reilly, Cohen, & Braver)
6:30-	Evening Cookout

<u>Friday, July 11</u>

7:30-8:00	Breakfast
8:00-8:40	Anders Ericsson & Peter Delaney "Long-Term Working Memory"
8:40-9:10	Discussion of Ericsson & Delaney (Discussion Leaders: Lovett & Reder)
9:10-9:50	Philip Barnard "Interactive Cognitive Subsystems Model of Working Memory"
9:50-10:20	Discussion of Barnard (Discussion Leader: Daneman)
10:20-10:40	Break
10:40-11:20	Walter Schneider "Connectionist/Control Architecture for Working Memory"
11:20-11:50	Discussion of Schneider (Discussion Leaders: Baddeley & Logie)
11:50-1:20	Lunch
1:20-2:00	Randy O'Reilly, Todd Braver, & Jonathan Cohen "A Biologically-Based Computational Model of Working Memory"
2:00-2:30	Discussion of O'Reilly, Braver, & Cohen (Discussion Leaders: Engle & Kane)
2:30-2:50	Break
2:50-3:30	Marcel Just "Working Memory, Working Brain: A Neural-Systems-Based Theory of Working Memory"
3:30-4:00	Discussion of Just & Carpenter (Discussion Leader: Cowan)

Saturday, July 12

7:30-8:00	Breakfast
8:00-8:40	David Meyer & David Kieras "Insights into Working Memory from the Perspective of Computational Cognitive Architectures for Modeling Human Performance"
8:40-9:10	Discussion of Meyer & Kieras (Discussion Leader: Just)
9:10-9:50	Meredyth Daneman & Irene Rukavina "Working Memory and Knowledge Acquisition in Educational Settings: An Applied Perspective"
9:50-10:20	Discussion of Daneman & Rukavina (Discussion Leaders: Young & Lewis)
10:20-10:45	Break
10:45-11:15	Com mentary 1: Alice Healy Basic Mechanisms and Representations in Working Memory The Relationship of Working Memory to Long-Term Memory
11:15-11:45	Discussion of the Healy Comm entary
11:45-1:15	Lunch
1:15-1:45	Commentary 2: Tim Salthouse The Nature of Working Memory Limitations The Relationship of Working Memory to Attention
1:45-2:15	Discussion of the Salthouse Commentary
2:15-2:45	Commentary 3: Mary Hegarty The Unitary vs. Non-Unitary Nature of Working Memory The Role of Working Memory in Complex Cognitive Activities
2:45-3:15	Discussion of the Hegarty Commentary
3:15-3:35	Break
3:35-4:05	Commentary 4: Bruce Pennington The Control and Regulation of Working Memory; The Biological Implementation of Working Memory
4:05-4:35	Discussion of the Pennington Commentary
7:00-	Banquet

Sunday, July 13

7:30-8:00	Breakfast
8:00-8:30	General Commentary 1: Alan Baddeley
8:30-9:00	General Commentary 2: Walter Kintsch
9:00-10:00	Group Discussion (Moderators: Akira Miyake & Priti Shah)
10:00-10:20	Coffee Break
10:20-11:20	Continuation of Group Discussion
11:20-	End of the Symposium

Symposium Highlights.

The most important outcome of the symposium was the success of the special features discussed above, that were designed to facilitate systematic theory comparison. As we hoped, the features supported active communication and collaborative problem solving among participants during the symposium. At the end of the symposium, it was clear that

there was a significantly advance in our theoretical understanding of the basic mechanisms and processes of working memory, and significantly increased scientific consensus of leading researchers in the field.

Specifically, during the course of the symposium a number of common themes gradually emerged that were embraced by essentially all the invited participants. Some of the common themes (Themes 4 and 5) are indeed surprising in that neither the organizers nor the individual participants anticipated them before the symposium took place. Below, we list these common themes that reflect the general consensus of the participants.

1) Working memory is not really a separate box in the mind or the brain.

This point was clear in essentially all the presentations. This consensus shows that current models of working memory go far beyond the traditional view of short-term memory (e.g., Waugh & Norman, 1965) that characterized it as a separate rehearsal buffer that is literally separate structurally from other memory stores. This traditional view, still strongly endorsed by general psychology textbooks, go agaist current conceptions of working memory.

2) Working memory's active maintenance function is in the service of complex cognition

This point is another sign of the demise of the traditional conception of short-term memory. In traditional models, maintenance functions are considered relatively passive and its purpose is primarily for memorizing (e.g., remembering phone numbers temporarily). Although many current models of working memory can explain such memory phenomena, all the models essentially adopt the view that the process of maintaining information is active and is in the service of complex cognitive activities. Current models do not view memory and cognition as completely separate; they are closely intertwined.

3) Working memory includes some control mechanisms

Another feature of models of working memory for which there is greater consensus following the symposium has to do with the notion of executive control. Although some traditional models included "control" mechanisms (e.g., Atkinson & Shiffrin, 1968), their capabilities were restricted to pure memorization functions. Current models have broadened the scope of control mechanisms and treat them as an essential and integral part of the working memory system.

4) Capacity limits reflect multiple factors

Unlike earlier conceptions of short-term memory (e.g., Miller, 1956) that tended to postulate one mechanism as if it were the sole capacity-limiting factor, the conceptions of working memory that were presented at the symposium seem to adopt the view that working memory limitations are likely to reflect multiple factors and may even be an emergent property, rather than a unitary limit inherent to the system.

5) Long-term knowledge and skills play an integral (if not the only) role in working memory performance

Another clear outcome of the symposium was consensus that the relationship between long-term memory and working memory needs to be reconceptualized. Most theorists at the symposium agreed that working memory is fundamentally inseparable from long-term memory in the sense that long-term knowledge and skills can be used as supplement the

limited working memory capacity and also that even the simplest tasks (such as word span) can reflect the contribution of long-term knowledge and skills.

6) Working memory requires the cooperation of different areas of the brain including the prefrontal cortex

A final issue of emerging consensus, based on the discussion at the sympoisum, is that various brain areas work together, at least partly under the "supervision" of the prefrontal cortex to produce working memory phenomena. This point is important because it contradicts the still-prevalent "separate box" view of working memory. Working memory phenomena require the dynamic cooperation of many areas of the brain, depending on the domains of the processing.

In summary, the discussion at the symposium clearly indicated new areas of scientific consensus and theoretical progress in working memory. This scientific progress will be represented in the edited volume based on the papers presented in this symposium, *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control.*

Companion Volume.

The papers presented at the symposium, edited to include the new ideas from the sympsoium, will be published in an edited volume entitled *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control*, by Cambridge University Press, along with introductory and concluding chapters prepared by the editors, Akira Miyake and Priti Shah. We have received a final version of most of the chapters, and the book will be forwarded to the publisher during the month of December for review. The copy-editing process will take place during the winter of 1998, and the final preparations for publication will take place in the spring. The book will be available in November or December of 1998.

This book will include the following chapters, all based on work presented at the ONR funded symposium:

Chapter 1: Theoretical Issues in Working Memory Research
by Priti Shah & Akira Miyake

Chapter 2: Working Memory: The Multiple Component Model
by Alan D. Baddeley and Robert H. Logie

Chapter 3: An Embedded-Processes Model of Working Memory
by Nelson Cowan

Chapter 4: Individual Differences in Working Memory Capacity and What They Tell Us About Controlled Attention, General Fluid Intelligence and Functions of the Prefrontal Cortex.
by Randall W. Engle, Stephen Tuholski, & Michael Kane

Chapter 5: Modeling Working Memory in a Unified Architecture: An ACT-R Perspective
by Marsha C. Lovett, Lynne M. Reder, & Christian Lebiere

Chapter 6: Working Memory in the EPIC Architecture
by David Kieras and David Meyer

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